

Protons, Aerospace, and Electronics: A National Interest

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The Aerospace Corporation

Ad hoc proton “team” formed by NASA OSMA/NEPP along with Air Force Space and Missiles Center (AFSMC), NRO, and Department of Energy (DOE) with support from industry and university partners



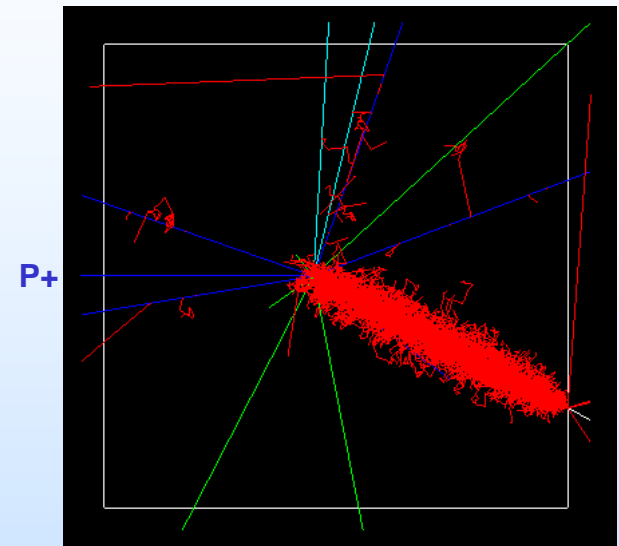
Acronyms

- Three Dimensional (3D)
- Air Force Space and Missiles Center (AFSMC)
- also know as (AKA)
- Automated Test Equipment (ATE)
- Californium (Cf)
- Crocker Nuclear Laboratory (CNL)
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- TBD - current year 2017 ??? (CY17)
- Displacement damage dose (DDD)
- Department of Energy (DOE)
- Device Under Test (DUT)
- Galactic Cosmic Rays (GCRs)
- Glenn Research Center (GRC)
- Hampton University Proton Therapy Institute (HUPTI)
- International Business Machines Corporation (IBM)
- Integrated Circuits (ICs)
- Indiana University Cyclotron Facility (IUCF)
- Johnson Space Center (JSC)
- Los Alamos Neutron Science Center (LANSCE)
- Lawrence Berkeley National Laboratories (LBL)
- linear energy transfer (LET)
- Cyclotron, linear accelerator (LINAC)
- Loma Linda University Medical Center (LLUMC)
- Massachusetts General Hospital (MGH) Francis H. Burr Proton Therapy Center
- Military Standard (MIL-STD)
- Math and Physics Sciences (MPS)
- n-type charge coupled device (n-CCD)
- NASA Electronic Parts and Packaging (NEPP) Program
- National Reconnaissance Office (NRO)
- Office of Safety and Mission Assurance (OSMA)
- research and development (R&D)
- South Atlantic Anomaly (SAA)
- SCRIPPS Proton Therapy Center (SCRIPPS)
- second (sec)
- Single Event Effects (SEE)
- Soft Error Rate (SER)
- size, weight, and power (SWaP)
- Texas A&M University (TAMU)
- to be determined (TBD)
- Total ionizing dose (TID)
- Tri-University Meson Facility (TRIUMF)
- University of Maryland Proton Therapy Center, Baltimore (U MD)
- University of California at Davis (UCD)
- University of Florida Proton Health Therapy Institute (UFHPTI)
- Van de Graaff (VDG)
- Van de Graaffs (VdGs)



Outline

- Abstract and Problem Statement
- Proton Effects on Electronics
- Potential Users
- Electronics Testing with Protons
- Domestic Proton SEE Facilities
- Questions



Sample 100 MeV proton reaction in a 5 um Si block.
Reactions have a range of types of secondaries and LETs.
Complicating statistics and testing.
(after Weller, *Trans. Nucl. Sci.*, 2004)



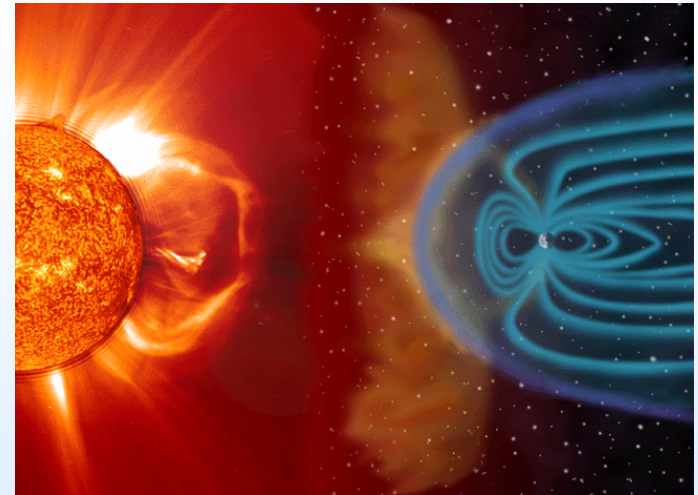
Abstract and Problem Statement

- **Abstract**
 - The aerospace and semiconductor industries lost ~2000 hours annually of research access when IUCF closed. An ad hoc team between the U.S. government and industry was formed to evaluate other facility options.
 - In this presentation, we will discuss:
 - Why aerospace, semiconductor manufacturers, and others are interested in proton facility access, as well as,
 - Some of the basics of a typical “test” for electronics.
 - We’ll conclude with the brief current status on progress.
- **Problem Statement (Space Electronics)**
 - Particle accelerators are used to evaluate risk and qualify electronics for usage in the space radiation environment
 - Protons simulate solar events and trapped protons in planetary magnetic fields

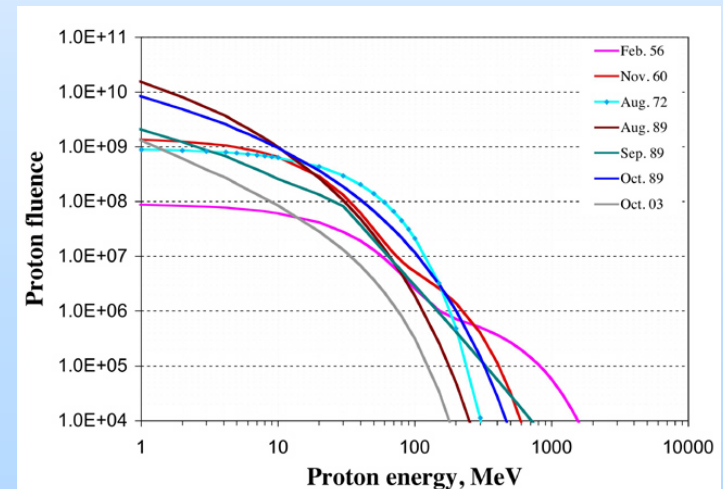


Protons and the Space Environment

- Three portions of the natural space environment contribute to the radiation hazard
 - Free-space particles
 - Galactic Cosmic Rays (GCRs)
 - Solar particles
 - *Protons* and heavier ions
 - Trapped particles (in magnetic fields)
 - *Protons* and electrons including the earth's South Atlantic Anomaly (SAA)
- Hazard experienced is a function of orbit and timeframe



The sun acts as a modulator and source in the space environment,
after K. Endo, Nikkei Sciences



<http://journalofcosmology.com/images/StraumeFigure3a.jpg>



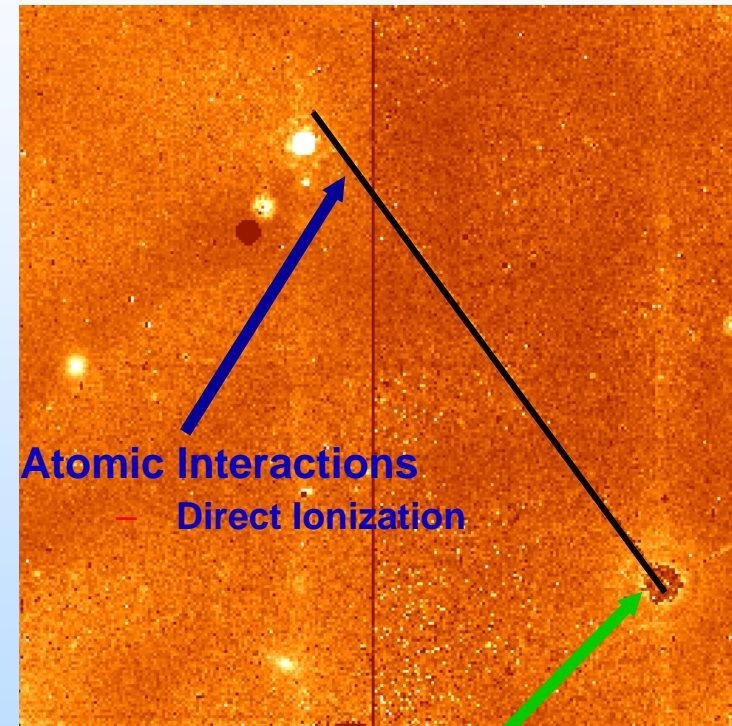
Radiation Effects and Electronics

- Particle accelerators/sources are used to evaluate risk and qualify electronics for usage in the space radiation environment
 - Long-term cumulative degradation (parametric and/or functional failures)
 - Total ionizing dose (TID)
 - Displacement damage dose (DDD)
 - Transient or single particle effects (Single event effects or SEE)
 - Soft or hard errors caused by proton (through nuclear interactions) or heavy ion (direct deposition) passing through the semiconductor material and depositing energy
 - Heavy ion tests on the ground are used to bound risk for space exposure to GCRs and some solar particles
 - **Protons** simulate solar events and trapped protons in planetary magnetic fields
 - SEE, TID, and DDD

Particle interactions with semiconductors

Image from the Space Telescope Science Institute (STScI), operated for NASA by the Association of Universities for Research in Astronomy

<http://www.stsci.edu/hst/nicmos/performance/anomalies/bigcr.html>



Interaction with Nucleus

- Indirect Ionization
- Nucleus is Displaced
- Secondaries spalled



Typical Ground Sources for Space Radiation Effects Testing

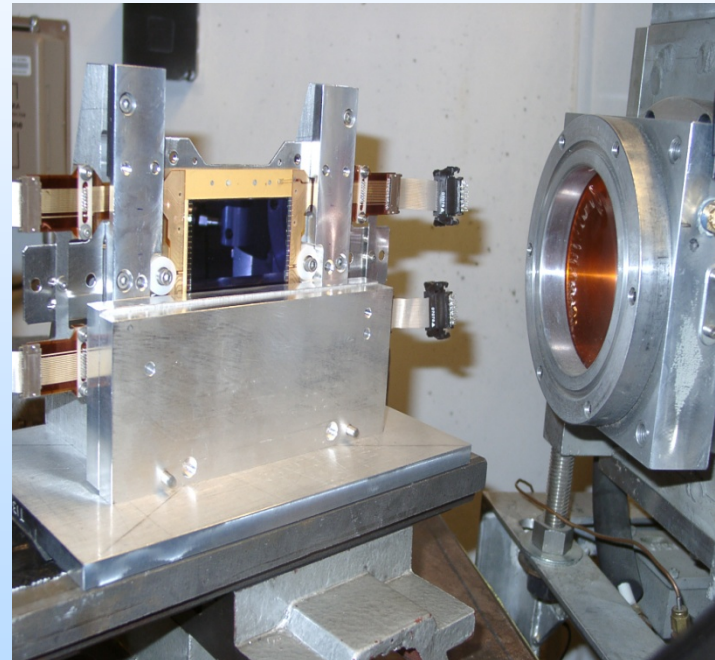
- Issue: TID
 - Co-60 (gamma), X-rays, **Proton**

- Issue: DDD
 - **Proton**, neutron, electron (solar cells)
 - Cyclotron, linear accelerator (LINAC), Van de Graaff (VDG) accelerator

- SEE (GCR)
 - Heavy ions
 - Cyclotrons, synchrotrons, VDGs
 - Lesser utility: Cf sources

- SEE (**Protons**)
 - Protons ($E > 30$ MeV) – primarily nuclear interactions
 - $E > 200$ MeV is “space sweetspot”
 - Protons (~ 1 MeV) – direct ionization effects in **very** sensitive electronics
 - Cyclotrons, synchrotrons

← *TID is typically performed at a local source with nearby automated test equipment (ATE). All others require travel and shipping with commensurate limitations/costs.*



Hubble Space Telescope Wide Field Camera 3
E2V 2k x 4k n-CCD
in front of Proton Beam at UC Davis
Crocker Nuclear Lab (CNL).

Photo by Paul Marshall, consultant to NASA



Space Electronics Users

NASA, other Government, Industry, University – International base

- **Space Electronic Systems – Flight Projects, Manufacturers**
 - Perform **qualification** tests on integrated circuits (ICs)
 - Perform **system validation/risk** tests on assembled hardware (boards/boxes)
- **Semiconductor Research**
 - Perform exploratory **technology sensitivity** tests on new devices/technology in advance of flight project usage or to **evaluate radiation hardening techniques**
 - Perform testing to **develop and define qualification (test) methods**
- **Semiconductor Industry – Product Development/Validation**
 - Performs tests on their new products for **MIL-STD qualification** as well as **preliminary sensitivity** tests on devices under development
 - Commercial terrestrial companies use protons for soft error rate (SER) testing in lieu of neutrons
 - Avionics, automotive, medical electronics, etc... test for safety critical and high reliability validation
- **Other Space Users**
 - Human Radiation Protection (biological sciences)
 - Material/shielding Studies (physical sciences)



Space and Other Researchers – *Growing Needs*

- **Space Users**
 - Increased use of commercial electronics for higher performing and smaller size, weight, and power (SWaP) systems.
Examples:
 - Advent of Small Space, aka, CubeSats – interest in risk reduction tests
 - Commercial Space – companies like SpaceX and OneWeb use protons for electronic assurance
- **Semiconductor industry – Increased reliability concerns from space to ground**
 - Advanced technologies (ex., <14nm feature size devices)
 - New architectures (3D structures)
 - New materials (roles of secondaries and fission products)
 - Replacement testing for terrestrial neutron effects (can do in hours what may take weeks in a neutron source)
- **Automotive**
 - Exponential growth industry for automotive electronics (driver assist, self-driving, etc...) – *Safety Critical* aspects



Sample Considerations for Electronics Proton Testing at Cyclotrons

- **Particle**

- Dosimetry/particle detectors
- Uniformity
- Energy mapping to the space environment
- Particle localization
- Stray particles (neutrons, for example)
 - Beware of “scatter” design
- Particle range
- Flux rates and stability
- Beam structure
 - Beam spills

- **Practical**

- Cabling
- Thermal
- Speed/performance
- Test conditions
- Power
- Mechanical
- Staging area
- Shipping/receiving
- Activated material storage
- Operator model (who runs the beam)



Patient vs. Electronics Proton Exposure

Patient

- **Measurement**
 - Dose (tissue/water)
- **Beam penetration**
 - Use Bragg peak to STOP beam in patient
- **Exposure stop**
 - Cumulative dose
- **Target size**
 - Tumor
- **Beam delivery**
 - Pencil beam, wobble, uniform scan or fixed point/scatter
- **Beam timing structure**
 - Timing less important
- **Patient exposure**
 - A few minutes
- **Beam movement**
 - Gantry or fixed

Electronics (typical)

- **Measurement**
 - Dose (material – Si, SiO₂, GaAs, ...) and particle rates (Fluence -protons/cm², and flux - protons/cm²/sec)
- **Beam penetration**
 - Beam goes THROUGH target
 - Suggest having a beam stop behind target
- **Exposure stop**
 - Cumulative dose or Fluence or
 - Number of recorded events or degradation or
 - “Unusual” event or failure
- **Target size**
 - Single chip (1cmx1cm) to full assembly (20cm x 20cm or larger)
- **Beam delivery**
 - Prefer fixed point/scatter
- **Beam timing structure**
 - When particle arrives versus electronics operation CAN be important (but not always)
- **Target exposure**
 - Seconds to minutes to ??? Depending on STOP criteria – usually under 2 minutes
 - Often MANY exposures (test runs) per target (10's to 100's)
- **Beam movement**
 - Fixed



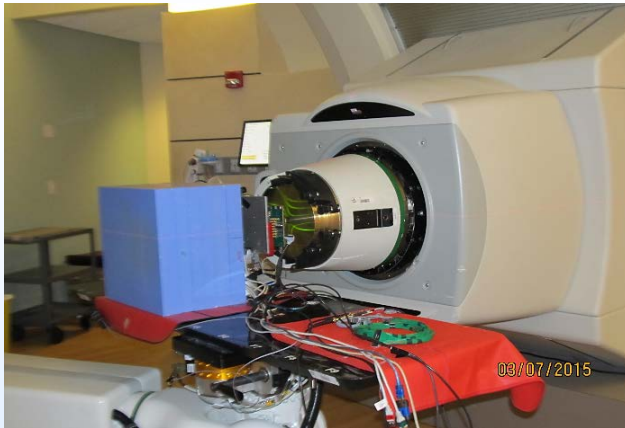
Study Team Desired Proton Test Capabilities (nominal)

- Energy range:
 - 125 MeV to > 200 MeV
- Proton flux rates:
 - $1e7$ p/cm²/sec to $1e9$ p/cm²/sec
- Test fluences:
 - $1e9$ p/cm² to $1e11$ p/cm²
- Irradiation area:
 - Small (single chip ~ 1cm) to board/assembly > 15cm x 15cm
- Beam uniformity:
 - >80%
- Beam structure:
 - Cyclotron *preferred* (random particle delivery over time)
 - Pulsed beam structure acceptable for *many* (but not all) applications
 - Fixed spot or scatter (random particle delivery over area)
 - Scanning beams MAY be acceptable but need to consider device or system under test operations versus timing of beam spots

Note: there are always users looking for outside of the above



Pretty Pictures from Testing (1)



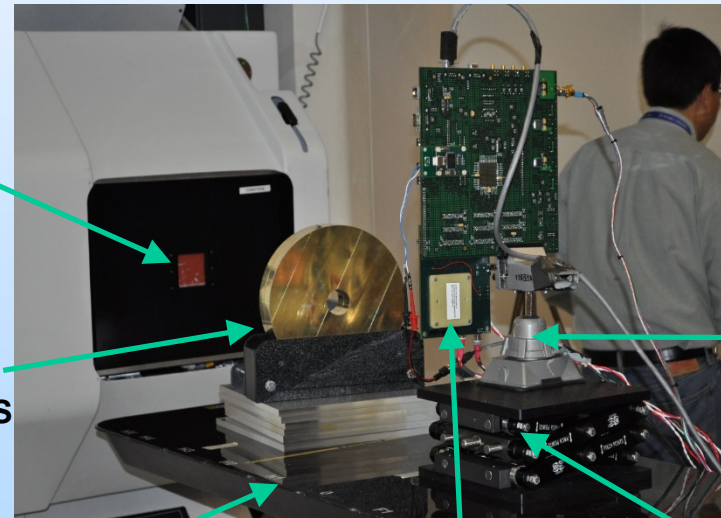
**Northwestern Medicine
Chicago Proton Center.**
Big blue block is the beam
stop.
Not all facilities thought
one was necessary.

SCRIPPS Proton Center.

Beam comes out here

Brass collimator
supplied by SCRIPPS

Robotic patient sled
supplied by SCRIPPS



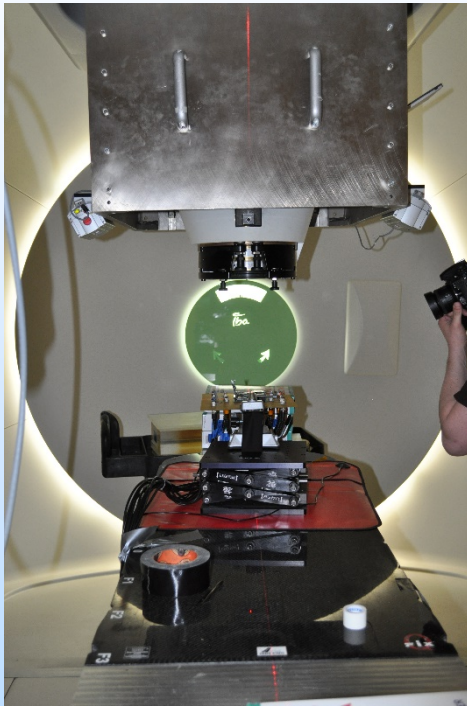
Clamp
(NASA equipment)

Device Under Test Table jack (NASA equipment)



Pretty Pictures from Testing (2)

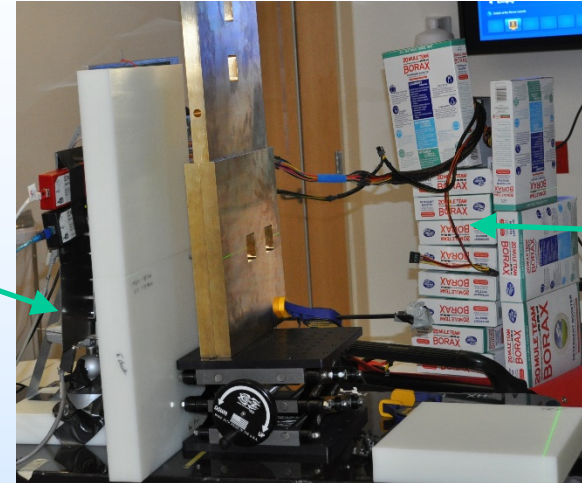
HUPTI



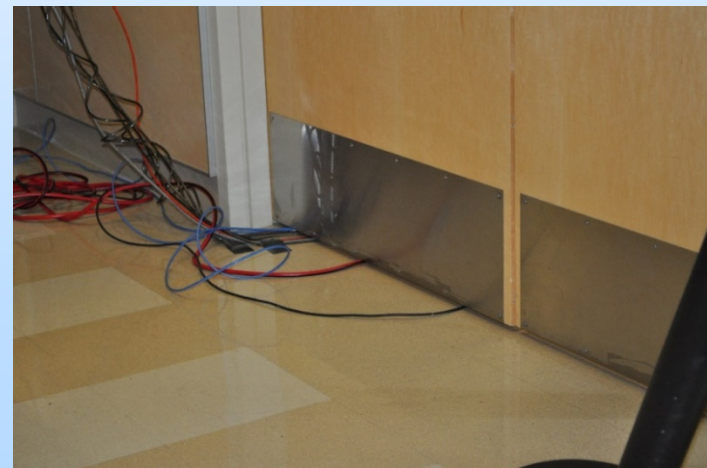
Gantry was rotated for vertical beam line.
The floor was the beam stop.

Typically, cables are run from target area to user/control area for monitoring and control of test electronics.

SCRIPPS



Neutron protection
For ancillary test equipment
in the target room

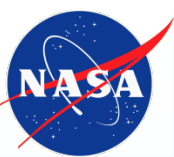




“Status” on Where We Test

- **The long-time facilities (used prior to IUCF shutdown)**
 - Massachusetts General Hospital (MGH) Francis H. Burr Proton Therapy Center
 - Tri-University Meson Facility (TRIUMF) – Vancouver, CAN
 - James M. Slater, M.D. Proton Treatment and Research Center at Loma Linda University Medical Center (LLUMC)
- **Newer locations**
 - SCRIPPS Proton Therapy Center
 - Northwestern Medicine Chicago Proton Center
- **Coming “soon”**
 - Cincinnati Children’s Proton Therapy Center
 - Mayo Clinic Proton Beam Therapy Program, Rochester, Minnesota
 - The Roberts Proton Therapy Center at University of Pennsylvania Health System
- **Possibilities**
 - Hampton University Proton Therapy Institute, Hampton, Virginia
 - Maryland Proton Treatment Center, Baltimore, Maryland
 - M.D. Anderson Cancer Center's Proton Center, Houston

Always open to discussions with ANY location



Questions?